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Effects of consolidation stress state on normally consolidated clay

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ABSTRACT: The effect of consolidation stress state on the stress-strain and strength characteristics has been studied from experiments on undisturbed block samples of a natural, normally consolidated clay known as San Francisco Bay Mud. The results of experiments on K_0-consolidated, hollow cylinder specimens and on isotropically consolidated, cubical specimens, both tested in triaxial compression and extension, clearly showed the influence of the undisturbed fabric as well as the effect of the initial consolidation stress states. While the K_0-consolidated specimens appeared to retain their original fabric and exhibit relatively stiff and strong behavior, the isotropically consolidated specimens showed signs of fabric alterations and weakening. Both the undisturbed fabric and the initial K_0-consolidation contribute to a response that may be described as cross-anisotropic.

1 INTRODUCTION

The structure and behavior of natural clays are the result of their geologic history, and in particular, of their depositional environment, preconsolidation history, aging effects and thixotropic hardening, cementation and weathering, leaching and other chemical phenomena. A laboratory investigation was undertaken to study the influence of consolidation stress state on the strength and deformation characteristics of a natural, normally consolidated clay known as San Francisco Bay Mud. Specimens were trimmed from undisturbed block samples of this soft, moderately sensitive clay and then consolidated under isotropic and K_0-stress states and sheared under undrained conditions in triaxial compression and extension. These experiments were part of a larger project performed to evaluate effects of cross-anisotropy and stress rotation on the soil behavior.

2 SAMPLING AND PREPARATION OF SPECIMENS

Twenty large cylindrical block samples of San Francisco Bay Mud were obtained from an excavation in reclaimed tidelands at a site located 1.6 km south of the San Francisco International Airport. All samples were obtained by pressing thin-walled tubes into a horizontal bench prepared in the excavation at a depth of approximately 6.5 m below the ground surface. Both the diameters and the lengths of the tubes were 30.5 cm. After insertion, each tube with the sample inside was excavated, sealed at the ends, transported to the laboratory, and stored in a humidity room until it was used for testing. The details of the sampling procedure were explained by Kirkgard and Lade (1991).

The in-situ preconsolidation pressure of the undisturbed samples was estimated at approximately 70 kPa, and torvane and UU-tests revealed undrained shear strengths of the soft clay to be generally less than 35 kPa. To alleviate concern that the clay would tend to deform and buckle when trimmed into a thin-walled hollow cylinder specimen, it was decided to preconsolidate all but one block sample one-dimensionally in the sample tubes. A setup similar to a floating ring consolidometer with double drainage was produced using porous plastic sheets at the ends of the sample. A vertical consolidation pressure of 100 kPa was adopted for all but one block sample. The latter was used to check whether preloading of the clay might alter the clay fabric and overshadow the effect of the stress history in the natural clay. Any alteration would be similar to that previously experienced due to vertical K_0-consolidation. Testing of specimens with and without preconsolidation were presented by Kirkgard and Lade (1991), and the experiments showed that the alteration was negligible.

After the additional consolidation, the block sample was removed from the sample tube by carefully cutting the tube side wall and prying the tube open. To provide the necessary specimens for experimentation in triaxial, cubical triaxial, and hollow cylinder tests, the center portion of the cylindrical block sample was cut loose and removed. This was accomplished by placing each clay block on the base ring for the hollow cylinder specimen, inserting a long needle and a suspended wire through the sample, and cutting out a conically shaped sample by rotating the wire using the base ring as a guide.

Each rough hollow cylinder specimen was immediately fine-trimmed and prepared for testing. Six slices were cut from the perimeter of each of twelve cylinder samples and examined for evidence of fabric and its relation to the soil stratigraphy in the area of the San Francisco Bay from which the samples were obtained. The samples were then further trimmed to produce hollow cylinder specimens with outside diameter of 220 mm and inside diameter of 180 mm. This was done on a special trimming device that operates essentially as a lathe. The specimen stands upright on the base ring of the torsion shear apparatus, and rotates on a disc (like a record player), while knives were moved up and down along the inside and outside surfaces using a motorized rack-and-pinion setup to trim the specimen.

The center portions of the block samples were appropriately wrapped, sealed, and stored in a humidity room for later testing. Two cubical specimens with side length of 76 mm were trimmed from each center portion. The results of the experiments performed on the cubical specimens are briefly reviewed below.

3 PREVIOUS STUDIES OF SAN FRANCISCO BAY MUD

Standard identification tests performed on the San Francisco Bay Mud produced a particle size distribution with about 45% clay particles and 55% silt particles, a liquid limit of 85 and a plastic limit of 48, and an activity of 0.82. Based on weight and volume measurements on the undisturbed block samples, the natural Bay Mud at the depth sampled exhibited a total unit weight of 1.44 g/cm^3. The average in-situ water content was 98.5%, and the liquidity index was therefore 1.36. Following preconsolidation the average total unit weight was 1.49 g/cm^3 and the average water content was 85.4%. The specific gravity ranged from 2.45 to 2.70 with an average of 2.55. The lower values may be related to the presence of organic material. The average content of organic material determined by ignition (ASTM 1989) was 1.3%. The sensitivity of this clay was reported by Duncan and Seed (1966) to be eight, whereas in-situ tests by Bonaparte and Mitchell (1979) indicated the sensitivity to be about five to six. The combination of pore fluid salt concentration and soil sensitivity obtained for the clay agrees well with values reported by Bjerrum (1954) for Norwegian marine clays.

In the experiments previously presented (Kirkgard and Lade, 1991, 1993) the cubical specimens were isotropically consolidated and sheared under undrained conditions in triaxial and cubical triaxial equipment to study the anisotropic behavior under axisymmetric and three-dimensional conditions without stress rotation. The principal stresses were applied parallel and perpendicular to the vertical axis in the field. A preliminary study of soil fabric, stratigraphy, and isotropic consolidation of specimens oriented at different horizontal directions relative to north revealed that the clay was truly anisotropic with three orthogonal planes of symmetry and with bedding planes inclined at 6^0 to 7^0 with horizontal. However, the clay could be characterized with sufficient accuracy for engineering purposes as a cross-anisotropic material with a vertical axis of symmetry.

The effective stress failure envelopes for vertical and horizontal specimens both showed considerable curvature, i.e. decreasing friction angles with increasing consolidation pressure, and the largest difference was obtained at the lower consolidation pressures, where effective friction angles were 4^0 to 5^0 lower for horizontal specimens.

Figure 1 shows the results of cubical triaxial tests performed with constant b-values in the three sectors of the octahedral plane in which $0^0 \leq \Theta \leq 180^0$. The cross-sections of the Mohr-Coulomb failure surface as well as Lade's isotropic failure surface (1977) are also shown in Figure 1 as guides for evaluation of the experimental results. The two failure criteria have been fitted to the strength of vertical specimens in triaxial compression represented by the friction angle of 30.6^0. The diagram is symmetric about the vertical axis, and the effective stress friction angles in the range of $120^0 \leq \Theta \leq 180^0$ are consistently about 5^0 smaller than in tests with similar b-values and values of Θ in the range of 0^0 - 100^0. A region of transition occurs for Θ-values in the range of 100^0 - 120^0. This indicates that the failure surface for San Francisco Bay mud exhibits cross-anisotropic characteristics.

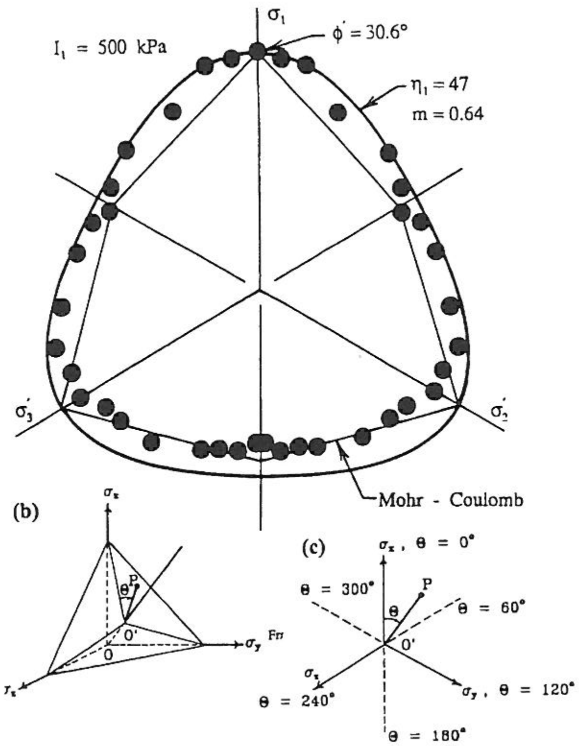


Figure 1 Traces of cross-anisotropic failure surface for San Francisco Bay Mud compared with the Mohr-Coulomb and Lade isotropic failure surfaces in octahedral plane, (b) principal stress space, and (c) octahedral plane with indication of angle Θ.

4 TESTS ON HOLLOW CYLINDER SPECIMENS

The torsion shear apparatus used for testing the hollow cylinder specimens has been described in detail by Lade (1981) and in summary form by Hong and Lade (1989a and b). Preparation procedures for sand and clay specimens have also been described by these authors.

If the inside and outside pressures in the hollow cylinder specimen are equal, then the tangential normal stress is equal to this radial stress, $\sigma_\theta = \sigma_r$, and in the absence of applied shear stresses, these lateral stresses are also equal to the intermediate and minor principal stresses,

$\sigma_\theta = \sigma_r = \sigma_2 = \sigma_3$. One test was performed as a triaxial compression test, and two tests were performed as extension tests on hollow cylinder specimens.

The specimens were first isotropically consolidated at an effective confining pressure of 100 kPa with a back pressure of 200 kPa, and the vertical deviator stress was then increased to achieve K_0-conditions. Final analysis of the state of stress in all the hollow cylinder specimens (including those tested in torsion shear) produced values of K_0 in the range from 0.52 to 0.62 with an average value of 0.56. In view of the actual effective friction angles obtained in the tests and correlations between K_0 and the friction angle, this value is a little high, but the experimental results obtained with a lower and more realistic K_0-value would likely not have been much different from those presented below.

5 EFFECT OF CONSOLIDATION STRESS STATE

Comparison of experimental results from cubical triaxial and hollow cylinder tests on cross-anisotropic soils can only be made for specimens loaded axisymmetrically along the axis of material symmetry, such that their results can be plotted in the triaxial plane containing the σ_1-axis and in the $(\sigma_z - \sigma_\theta)$-$\sigma_r$' plane . Figure 2 shows a comparison of effective stress paths for triaxial compression and extension tests on San Francisco Bay Mud. The results of the cubical triaxial compression tests with initial isotropic consolidation of σ'_c/p_a = 70, 125, and 175 have previously been presented by Kirkgard and Lade (1991, 1993). The hollow cylinder specimens were consolidated at K_0-stress states, and their undrained shearing were therefore initiated away from the hydrostatic axis, similar to that found in the ground. Each of the data sets from the cubical triaxial tests and from the hollow cylinder tests are consistent. Two cubical triaxial tests were performed for each of the two higher consolidation pressures, and they produced very similar results, as indicated by the effective stress paths in Figure 2. The test with the lowest confining pressure fits in the pattern of the other tests. Two triaxial extension tests with initial K_0-consolidation were conducted on hollow cylinder specimens, and their effective stress paths are also similar in shape, although not coinciding in the extension regime.

For normally consolidated, compressible soils, such as the soft clay tested here, the effective stress paths for undrained tests with zero overall volume change essentially outline the shape of the plastic yield surface. As undrained shearing occurs, the plastic yield surface is pushed out, thus producing a tendency for plastic volumetric compression. This tendency has to be matched by an equal amount of elastic volumetric expansion, and this is produced by a reduction in mean normal stress. The more compressible the soil, the closer the match between the effective stress path and the plastic yield surface. On the other hand, the yield surface is not traced if the stress path ventures into a region of plastic dilation.

Thus, the undrained tests can be used to study the effect of consolidation on the induced anisotropy by observing the shape of the effective stress paths. As has been observed before (see e.g. Ladd and Varallyay, 1965; Tavenas and Leroueil, 1977; and many others as presented in an excellent review by Leroueil, 1997), the consolidation stress state plays a major role in the behavior of natural clays. For a compressible clay like the normally consolidated San Francisco Bay Mud, Figure 2 clearly shows that the yield surfaces tend to be centered around the consolidation stress states. Thus, the isotropically consolidated cubical specimens have effective stress paths, and therefore yield surfaces, that tend to be centered around the hydrostatic axis, but Figure 1 indicates that the cross-anisotropic characteristics remain at the time of failure.

Figure 2 also shows that the K_0-consolidated specimens have their yield surfaces influenced by the anisotropic consolidation and are biased towards the K_0-line. However, the inherent fabric produces effective stress paths in the two extension tests that exhibit very little variation in effective major principal stresses in the extension regime, causing the effective stress paths to be vertical in the triaxial plane. This behavior deviates somewhat from results of similar tests presented in the literature (Leroueil, 1997). The results shown in Figure 2 indicate that effects of inherent and stress induced anisotropy both play roles in the behavior of the clay, whether isotropically or anisotropically consolidated. Thus, all aspects of the behavior are substantially affected by the initial consolidation stress state.

The results of the hollow cylinder tests with initial K_0-consolidation, and the cubical triaxial tests initially consolidated at an isotropic confining pressure of 125 kPa are studied further. These tests have effective stress paths that almost coincide at the hydrostatic axis in Figure 2. The pore pressure changes are measured in the direction of the hydrostatic axis and their signs (positive and negative) are indicated in this diagram by (+ve) and (-ve). The pore pressure changes due to shearing are positive in all tests except in the hollow cylinder extension tests. This by itself is not significant. Whether the pore pressure changes are positive or negative depends on the total stress paths imposed on the specimens. The pore pressures adjust to follow the effective stress path along which the volume change is zero. Figure 3 shows the stress-strain behavior, Figure 4 indicates the negative pore pressure changes, and Figure 5 shows the effective stress paths in a $(\sigma_z - \sigma_\theta)$-$\sigma_r$' plane for this group of tests.

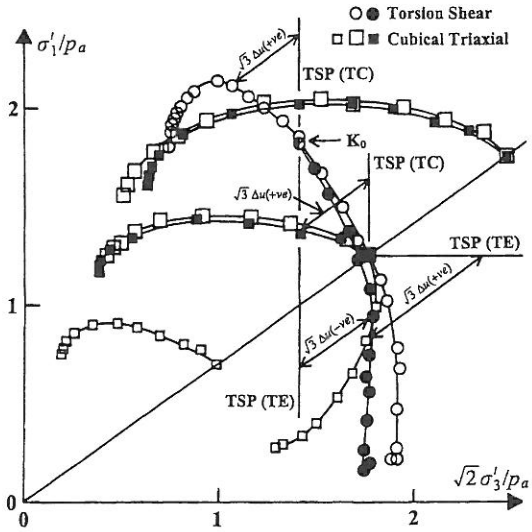
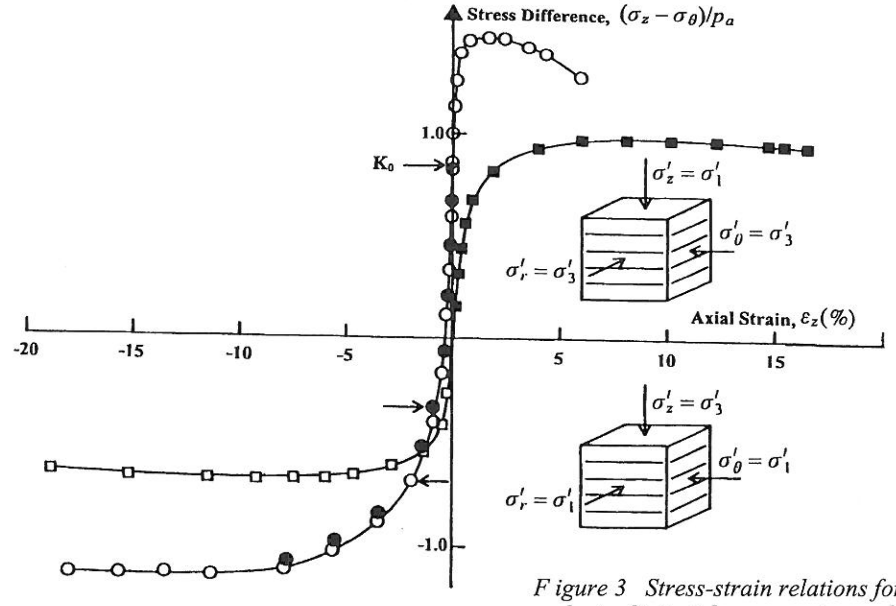


Figure 2 Effective stress paths in triaxial plane for undrained triaxial compression and extension tests with initial isotropic and K_0-consolidation performed on San Francisco Bay Mud.

Of special interest is the development of (negative) pore pressure changes in the hollow cylinder tests, because they control the shape of the effective stress paths. Starting at the K_0-condition, the pore pressure changes immediately become negative, and they reach their peak at 1 to 2% axial strain, as shown by arrows in Figure 4. They stay essentially constant thereafter, while the deviator stresses continue to reduce until effective stress failure occurs at much larger axial strains, as indicated in Figure 3. If the effective stress paths in the K_0-consolidated hollow cylinder specimens were to follow the effective stress path in the isotropically consolidated cubical specimen, the negative pore pressure changes would have to reduce towards zero and even become positive. This would tend to happen if the clay fabric were collapsing during shear, but this clearly did not occur. Both extension tests with initial K_0-consolidation show similar behavior, and one of the torsion shear tests, whose effective stress path runs very close to and almost parallel to the extension stress path, also shows negative pore pressure changes which suddenly become constant at very low axial strains. Thus, there is experimental corroboration regarding the type of behavior observed in the K_0-consolidated extension tests.

The shape of the plastic yield surface is related to the clay fabric and its anisotropy. Both Figures 2 and 5 show that the yield surfaces for the isotropically consolidated specimens are rounded and bend back towards the stress origin, while the yield surfaces for the K_0-consolidated specimens are less rounded and form an almost spherical cap with the center at the stress origin. Both the effective stress paths and the stress-strain relations shown in Figure 3 indicate that the K_0-consolidated specimens exhibit stiffer response in both compression and extension than the isotropically consolidated specimens. This may indicate that the fabric was partly changed, i.e. disturbed, by the isotropic consolidation, because more positive pore pressures developed during undrained shearing in these tests, most likely in response to further collapse of the already disturbed fabric. The tests with initial K_0-consolidation show stiffer response and this may indicate that the original clay fabric is better preserved in these specimens.

Consolidation to higher pressures, as performed in the sample tubes and in the test equipment, follows the concepts embedded in the SHANSEP procedure for reconstituting clay specimens (Ladd and Foot, 1974). In view of the findings presented here, it is possible that the initial



F igure 3 Stress-strain relations for undrained triaxial compression and extension tests with initial isotropic and K_0-consolidation performed on San Francisco Bay Mud.

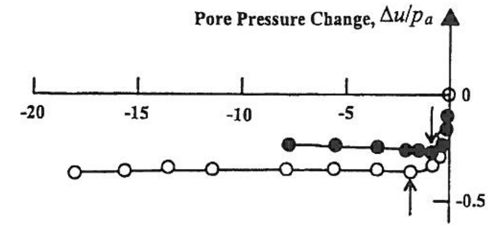


Figure 4 Pore pressure changes for undrained triaxial extension tests with initial K_0-consolidation performed on San Francisco Bay Mud.

one-dimensional consolidation in the sampling tube and the subsequent K_0-consolidation, from an initial vertical stress of about 70 kPa in the field to about 185 kPa in the hollow cylinder tests (for a vertical stress increase of 265%), may also have had disturbing effects on the response of the San Francisco Bay Mud. However, it is difficult to see how the effective stress paths, initiating from the K_0-state in Figures 2 and 5, could include effects of disturbance. The effective stress paths from the compression and the two extension tests form a continuous surface without a break at the K_0-state, and they show much stiffer response than the isotropic consolidated specimens. It is concluded that only minor disturbance, if any, derive from K_0-consolidation to higher stresses, while isotropic consolidation clearly alters the response of the initially intact San Francisco Bay Mud.

6 STRENGTH CHARACTERISTICS

6.1 Variation of Effective Friction Angle

Comparison of the friction angles from the K_0-consolidated hollow cylinder specimens with those obtained from the isotropically consolidated cubical specimens show considerable difference, as already indicated in Figures 2 and 5. The friction angles from cubical specimens in triaxial compression are approximately φ' = 38°, while that from the hollow cylinder test is about φ' = 34°. The friction angle in triaxial extension from the isotropically consolidated cubical specimen is about 33°, and those from the K_0-consolidated hollow cylinder specimens are around 50°. These high effective friction angles are supported by the other torsion shear tests performed with stress paths in the vicinity of the triaxial extension tests.

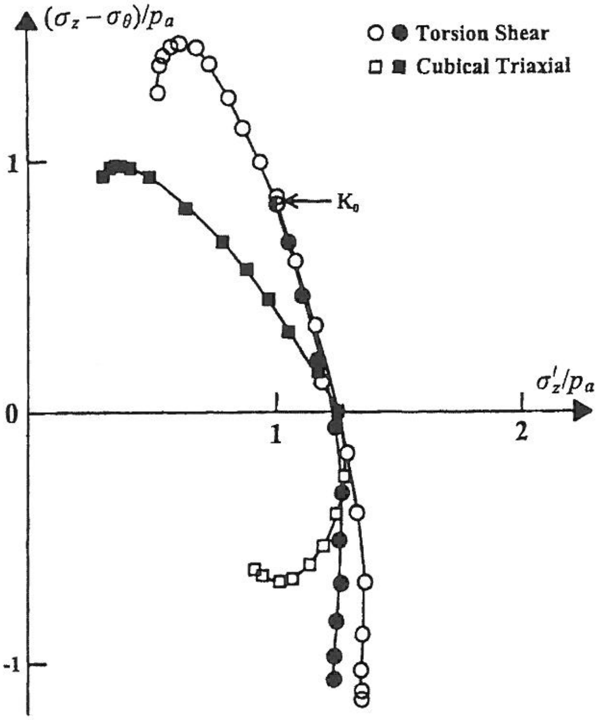


Figure 5 Effective stress paths shown in (σ_z - σ_θ)-σ_r' plane for undrained triaxial compression and extension tests with initial isotropic and K_0-consolidation performed on San Francisco Bay Mud.

Effects of the magnitude of the mean normal stress are present in the experimental results. Thus, the data shown in Figure 1 have been projected along the curved failure surface onto the octahedral plane corresponding to I_1 = 500 kPa, and the friction angle in triaxial compression is consequently 30.6°. But to the authors' knowledge, the only other difference between the cubical triaxial tests and the hollow cylinder tests is the difference in consolidation history, and this produced the large difference of 17° in the effective friction angle in triaxial extension. As mentioned above, it is possible that the isotropic consolidation has partially altered and weakened the clay fabric, and it is therefore likely that the cubical specimens produced effective friction angles that are affected by this alteration. On the other hand, the values obtained from the K_0-consolidated specimens seem to be unusually high for clays.

6.2 Variation of Normalized Undrained Shear Strength

The undrained shear strength may be normalized on the vertical consolidation stress from the K_0-consolidation. The highest value of normalized shear strength is obtained for vertical specimens, i.e. the usual and most convenient orientation of specimens tested in triaxial compression. In comparison, the normalized undrained shear strength in triaxial extension is approximately 80% of the value for the vertical specimen. Similar differences have commonly been observed for other natural clays.

7 CONCLUSION

The results of experiments on K_0-consolidated, hollow cylinder specimens and on isotropically consolidated, cubical specimens, both tested in triaxial compression and extension, clearly showed the influence of the undisturbed fabric as well as the effect of the initial consolidation stress states. While the K_0-consolidated specimens appeared to retain their original fabric and exhibit relatively stiff and strong behavior, the isotropically consolidated specimens showed signs of fabric alterations and weakening. Consequently, the stress-strain and strength results were significantly different for the two modes of consolidation. Both the undisturbed fabric and the initial K_0-consolidation contribute to a response that may be described as cross-anisotropic.

It is concluded that the most realistic investigations of the stress-strain and strength behavior of natural clays are performed on specimens carved from block samples and reconsolidated under K_0-conditions before testing.

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